Spin filtering through a double-bend structure

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We propose a simple scheme for the spin filter by studying the coherent transport of electrons through a double-bend structure in a quantum wire with a weak lateral magnetic potential which is much weaker than the Fermi energy of the leads. *Extremely large* spin polarized current in the order of *micro-Ampere* can be obtained because of the strong resonant behavior from the double bends. Further study suggests the roubustness of this spin filter.

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The rapid emerging field of spintronics promises to provide new advances that have a substantial impact on future applications.[1,2,3] Effective and efficient electrical spin injection of spin-polarized current into semiconductors is one of the major challenges in this field.[4,5,6] One method is to inject spin current through ideal ferromagnet/semiconductor interface. However, the polarization of the injected current is rather small due to the large conductivity mismatch.[7] The use of spin filters is therefore an alternative approach which can significantly enhance spin injection efficiencies. In some previous works, spin-selective barriers[8] or stubs[9] are essential to realize spin polarization (SP). Other methods such as quantum dot[10] and resonant tunneling diode[11] also have been reported. Very recently we also proposed a scheme of spin filter by utilizing the "band-gap" generated by the weak lateral magnetic modulations.[12] However, it is noted that the spin currents of these filters are relatively small.

In this letter we propose a new scheme of the spin filter which provides *exteramly large* spin current by utilizing the resonance in a double-bend structure with a uniform small magnetic field which can be realized by sticking a magnetic strip on top of the sample or using magnetic semiconductor. The effect of the bend discontinuity has been discussed in detail in a mode-matching theory by Weisshaar *et al.*[13] There it was shown that strong resonance effects are present in the transmission coefficient versus energy due to the presence of a perpendicular single right bend. They further showed that the effect of the second bend (*i.e.* a double-bend structure) is to add further fine resonances superimposed on the dominant resonance, with the width and the spacing in energy depending on the cavity of length L. We will show that this resonance effect can be effectively utilized to generate SP's.

A schematic of the double-bend structure is shown in Fig. 1. The spin dependent potential with Zeeman-like form $V_\sigma(x,y) = \sigma V_0 g(x,y)$ is applied on the double bends (regions B and C). Here $g(x,y) = 1$ if (x,y) locates at regions B and C , and 0 otherwise. σ is ± 1 for spin-up and -down electrons, respectively. V_0 denotes a spin-independent parameter for the strength of the potential. For $E_f \gg V_0$, spin-up and -down electrons experience different potentials: the spin-up electrons coherently transport through a "transparent" barrier while the spin-down ones do through a well. Therefore, spin polarized current can be obtained because of the mismatch of the resonances from the double bends of the spin-up and -down electrons.

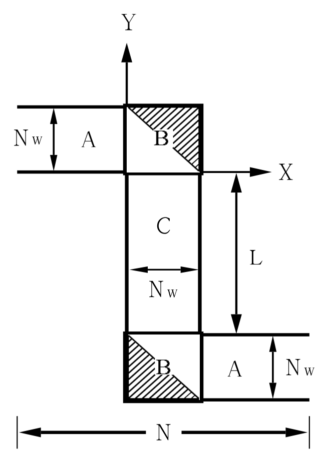

FIG. 1: Schematic of the spin filter in double-bend structure.

We describe the double-bend structure by a tight-binding Hamiltonian with the nearest-neighbour approximation:

$$H = \sum_{l,m,\sigma} (\epsilon_{l,m,\sigma} c^\dagger_{l,m,\sigma} c_{l,m,\sigma} + t_0 c^\dagger_{l,m+1,\sigma} c_{l,m,\sigma} + t_0 c^\dagger_{l+1,m,\sigma} c_{l,m,\sigma}) + \mathrm{H.C.}\ , \tag{1}$$

in which l and m denote the coordinates along the x- and y-axis respectively. $\epsilon_{l,m,\sigma} = \epsilon_0 + \sigma V_0$ $(= \epsilon_0)$ when (l,m) locates at the B and C regions (when (l,m) locates at the A region), denotes the on-site energy with $\epsilon_0 = -4t_0$. $t_0 = -\hbar^2/2m^*a^2$ is the hopping energy with m^* and a standing for the effective mass and the "lattice" constant respectively.

The spin dependent conductance is calculated using the Landauer-Büttiker[14] formula with the help

of the Green's function method.[15] The two-terminal spin-resolved conductance is given by $G^{\sigma\sigma'} = (e^2/h)\mathrm{Tr}[\Gamma_1^\sigma G_{1N}^{\sigma\sigma'+}\Gamma_N^{\sigma'} G_{N1}^{\sigma'\sigma-}]$ with Γ_1 (Γ_N) representing the self-energy function for the isolated ideal leads.[15] We choose the perfect ideal ohmic contact between the leads and the semiconductor. $G_{1N}^{\sigma\sigma'+}$ and $G_{N1}^{\sigma\sigma'-}$ are the retarded and advanced Green functions for the conductor, but with the effect of the leads included. The trace is performed over the spatial degrees of freedom along the y-axis. The spin dependent current within an energy window $[E, E+\Delta E]$ is given by $I_\sigma = \int_E^{E+\Delta E} G^{\sigma\sigma}(E)dE$.

We perform a numerical calculation for a quantum wire with width N_w. A hard wall potential is applied in this transverse direction which makes the lowest energy of the nth subband (mode) be $\epsilon_n(N_w) = 2|t_0|\{1-\cos[n\pi/(N_w+1)]\}$. $a = 9.53$ Å which makes $|t_0| = 1$ eV throughout the computation. We take the Zeeman splitting energy $V_0 = 0.01|t_0|$.

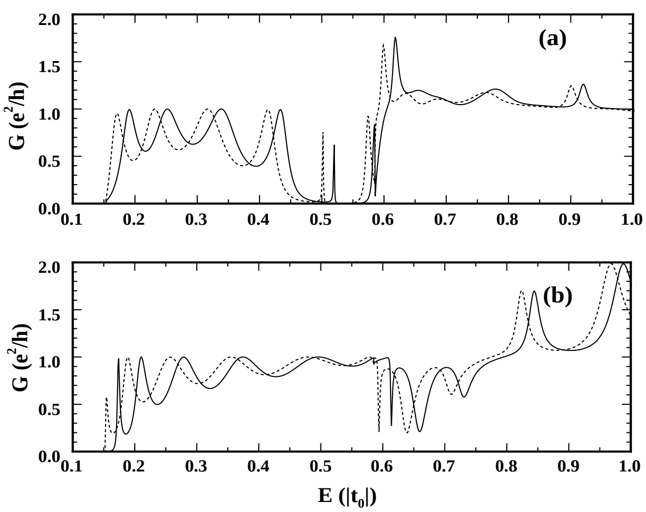

FIG. 2: Conductance versus the energy of the electron for (a) the double-bend structure in Fig. 1 and (b) the same structure in (a) but with the corners (shadowed areas in Fig. 1) cut. $L = 20a$. Solid curve: $G^{\uparrow\uparrow}$; Dotted curve: $G^{\downarrow\downarrow}$.

In Fig. 2(a) the conductance is plotted as a function of the Fermi energy E of the leads with $N_w = 7a$ and cavity length $L = 20a$. Both the single and the double modes are included in the figure. It is seen from the figure that SP is obtained from each energy window in which the mismatch of the resonances for electrons with different spin directions occurs. Spin current densities can be obtained from the energy window $[0.51|t_0|, 0.525|t_0|]$ with $I_\uparrow^{SP} = I_\uparrow - I_\downarrow \approx 61.7$ nA for spin-up current and from the window $[0.49|t_0|, 0.51|t_0|]$ with $I_\downarrow^{SP} = I_\downarrow - I_\uparrow \approx 63.7$ nA for spin-down current, each with 100 % SP. SP can also be obtained from other energy intervals due to the mismatch of the resonance peaks for different spin. Particularly if one chooses the energy window $[0.425|t_0|, 0.49|t_0|]$, one gets an *extremely large* spin current $I_\uparrow^{SP} \approx 0.635$ μA. This large spin current scales with the magnitude of the applied potential V_0. If one takes an even smaller number $V_0 = 0.005|t_0|$ ($0.001|t_0|$), one also gets a large current $I_\uparrow^{SP} \approx 0.347$ μA (0.072 μA) by choosing a suitable energy window on the edge of the gap.

The spin-independent gap near $E = 0.55|t_0|$ corresponds to the anti-resonance gap due to the reflection of the bend structure. By cutting off the corners (the shadowed areas in Region B shown in Fig. 1) from the both bends, one can see from Fig. 2(b) that the gap disappears and one also loses the energy window for the large spin current.

In order to understand the resonance feature of the double bends, we calculate the conductance with $L = 10a$ and $L = 30a$. By comparing Fig. 3 and Fig. 2(a), one finds that the number of the resonant peaks increases with the cavity length L. When the wave length of the incident electron $\lambda = 2\pi a\sqrt{\frac{|t_0|}{E-\epsilon_1(N_w)}}$ satisfies the standing wave condition $\frac{j}{2}\lambda = L + 2N_w$ with $(j = 1, \cdots, j_{max})$, the conductance reaches the maximum. It is therefore easy to see that within the fixed energy interval of the first subband $(0.15|t_0| < E < 0.56|t_0|)$, a larger bend distance L corresponds to a larger j_{max} and therefore more resonance peaks.

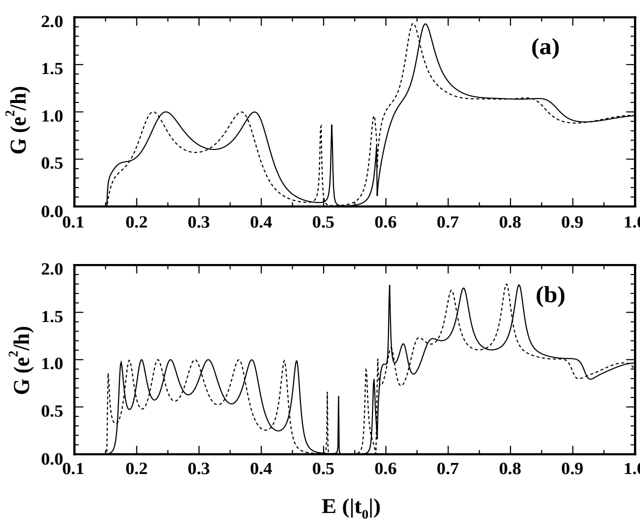

FIG. 3: Conductance versus the energy of the electron with different L: (a) $L = 10a$; (b) $L = 30a$. Solid curve: $G^{\uparrow\uparrow}$; Dotted curve: $G^{\downarrow\downarrow}$.

We also check the roubustness of the spin filter proposed above by including Anderson disorder to investigate its effect on the spin polarized currents. We take the strength of the disorder to be $W = 0.05|t_0|$, five times of the potential V_0. We still obtain a large spin polarized current $I_\uparrow^{SP} \approx 0.545$ μA.

Finally we point out that the scheme of the spin filter proposed in this letter can be generalized to any structure in which the conductance oscillates with the energy

of the incident electrons. Then by applying a small spin-dependent potential, one gets the mismatch of the resonance peaks for different spins and hence the SP. However, if one wishes to obtain a filter which can give a large spin current, then a anti-resonance gap is essential in the structure.

In summary, we have proposed a simple scheme for spin filter by studying the coherent transport through double-bend structure with a lateral magnetic potential. Extremely large spin current is predicted from this structure. The magnetic potential can be realized by sticking the magnetic strip on top of the sample or using magnetic semiconductors. This spin filter is very robust to the disorder.

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